

# NuMI Analysis

*Sharon Seun*

## Outline

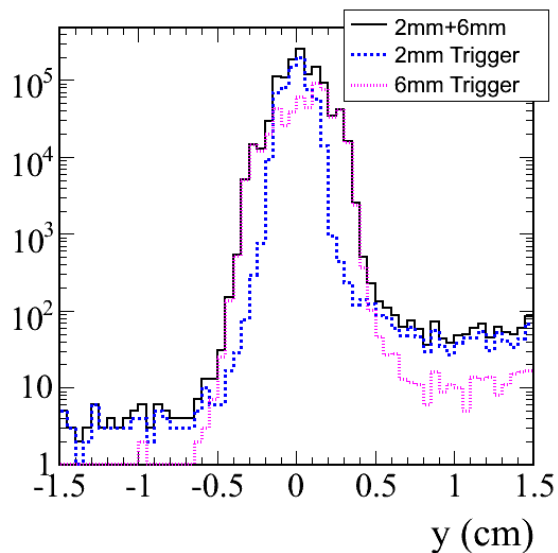
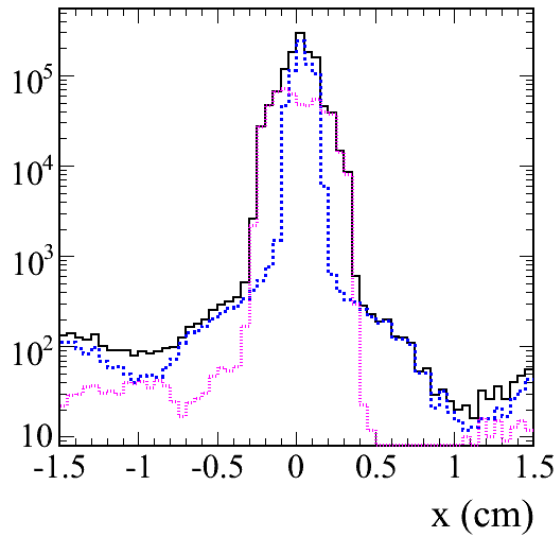
1. Introduction
2. Data Selection & PID
3. Analysis Procedure
4. NuMI Target Results
5. Conclusion

# Introduction

- Goal of this analysis is to measure the production ratios from the NuMI target
  - $\pi^-/\pi^+$ ,  $K^-/K^+$ ,  $\pi^+/K^+$ ,  $\pi^-/K^-$
- Data used
  - 2 million NuMI target
  - Full data set from summer 2005
- Monte Carlo simulation
  - FLUKA-2006 for proton-NuMI interaction
  - Geant for tracking along the beam line and through the detectors
- Reconstruction
  - Analysis using tracking and RICH PID only

# **Data Selection & Particle Identification**

# Beam Selection



- NuMI trigger selection

*All 2 mm trigger*

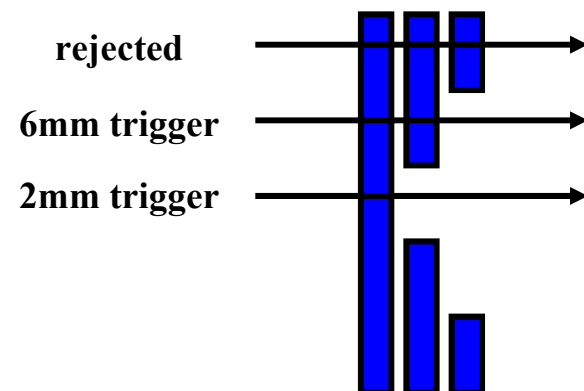
*All 6 mm trigger*

- Beam selection

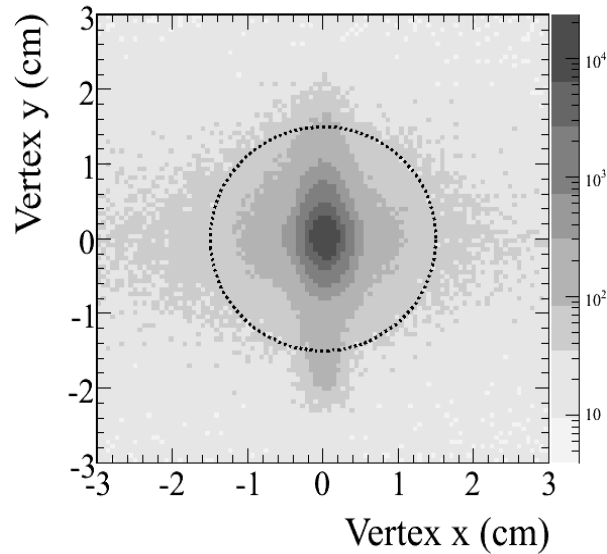
$$|x| < 0.45 \text{ cm}$$

$$|y| < 0.50 \text{ cm}$$

Only < 0.5% of events is cut



# Track Selection

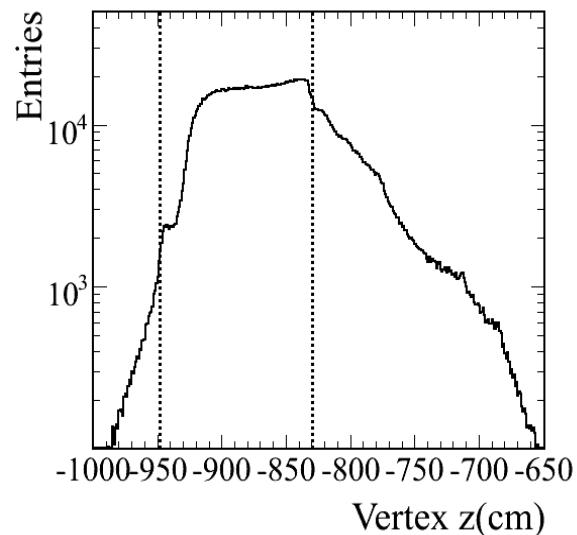


- Interaction vertex  
 $\geq 2$  tracks from a vertex
- Vertex from target  
Radial cut:

$$r \leq 1.5 \text{ cm}$$

Longitudinal cut:

$$\text{front} \leq z \leq \text{end of target}$$



# Momentum Selection

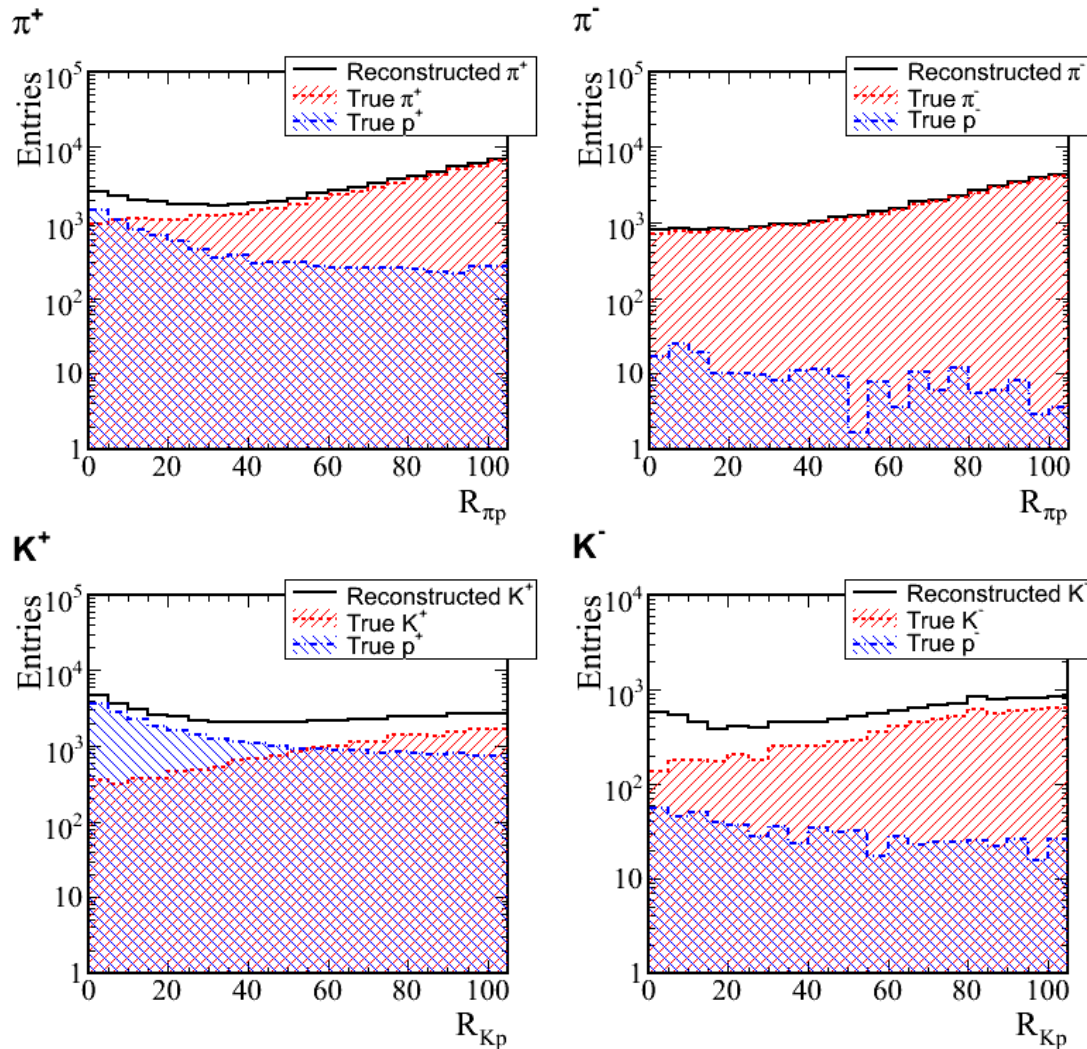
Due to limitations imposed by the detector acceptance and particle limitation of the RICH, only consider reconstructed particle with

$$20 \text{ GeV}/c < p_z < 90 \text{ GeV}/c$$

$$p_T < 2 \text{ GeV}/c$$

Binning Scheme ( $p_z, p_T$ )		$p_z \text{ (GeV}/c\text{)}$				
		20-24	24-31	31-42	42-60	60-90
$p_T \text{ (GeV}/c\text{)}$	1.0-2.0		(1,4)	(2,4)	(3,4)	(4,4)
	0.6-1.0	(0,3)	(1,3)	(2,3)	(3,3)	(4,3)
	0.4-0.6	(0,2)	(1,2)	(2,2)	(3,2)	(4,2)
	0.2-0.4	(0,1)	(1,1)	(2,1)	(3,1)	(4,1)
	0.0-0.2	(0,0)	(1,0)	(2,0)	(3,0)	(4,0)

# Particle Classification



- Log-likelihood ratio

$$R_{xy} = \text{Log } x - \text{Log } y$$

- Cuts

- Tracks classified based on largest likelihood
- Additional conditions for certain particles

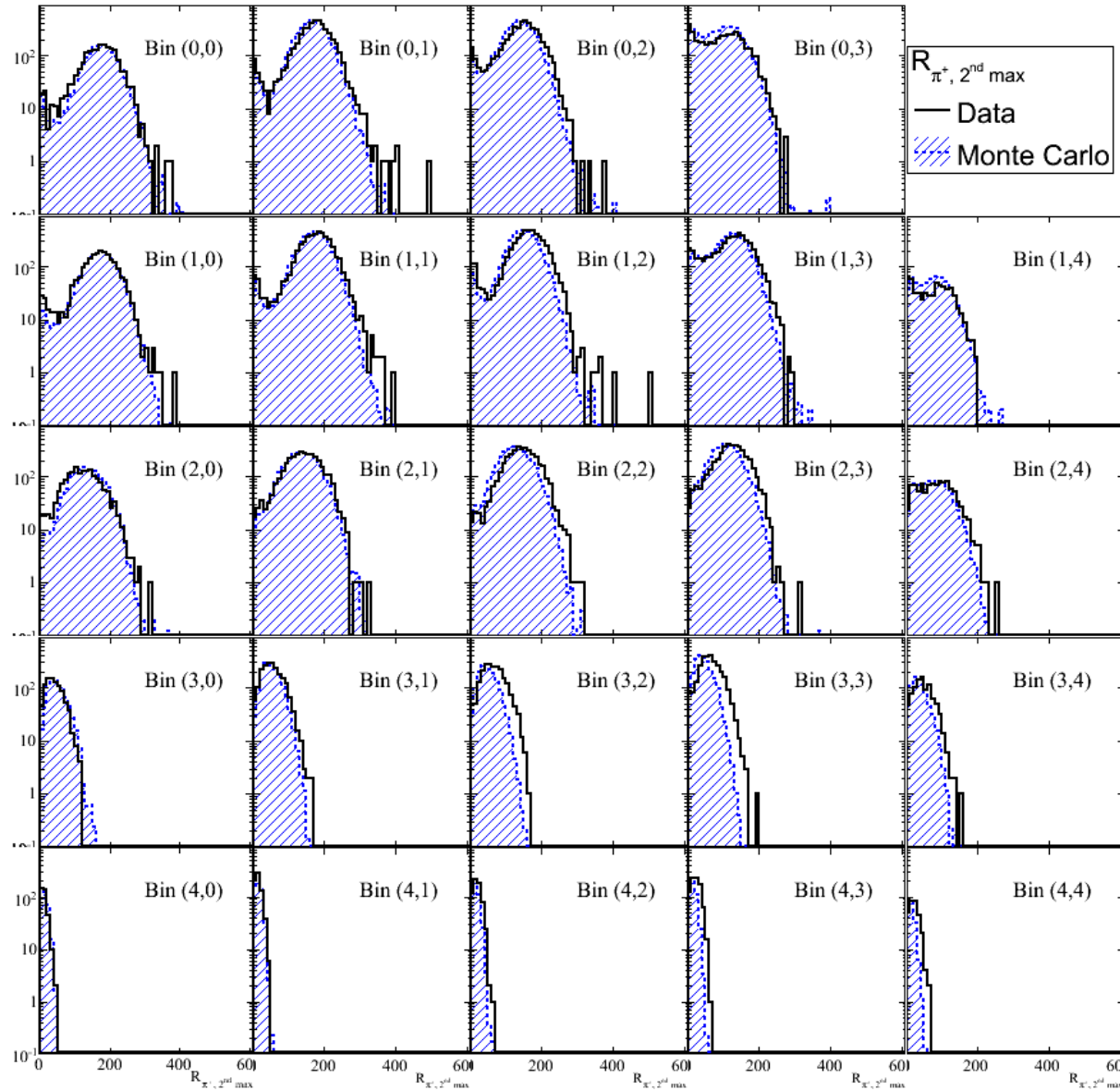
$$R_{\pi^+ p^+} > 10 \Rightarrow \text{select } \pi^+$$

$$R_{K^+ p^+} > 35 \Rightarrow \text{select } K^+$$

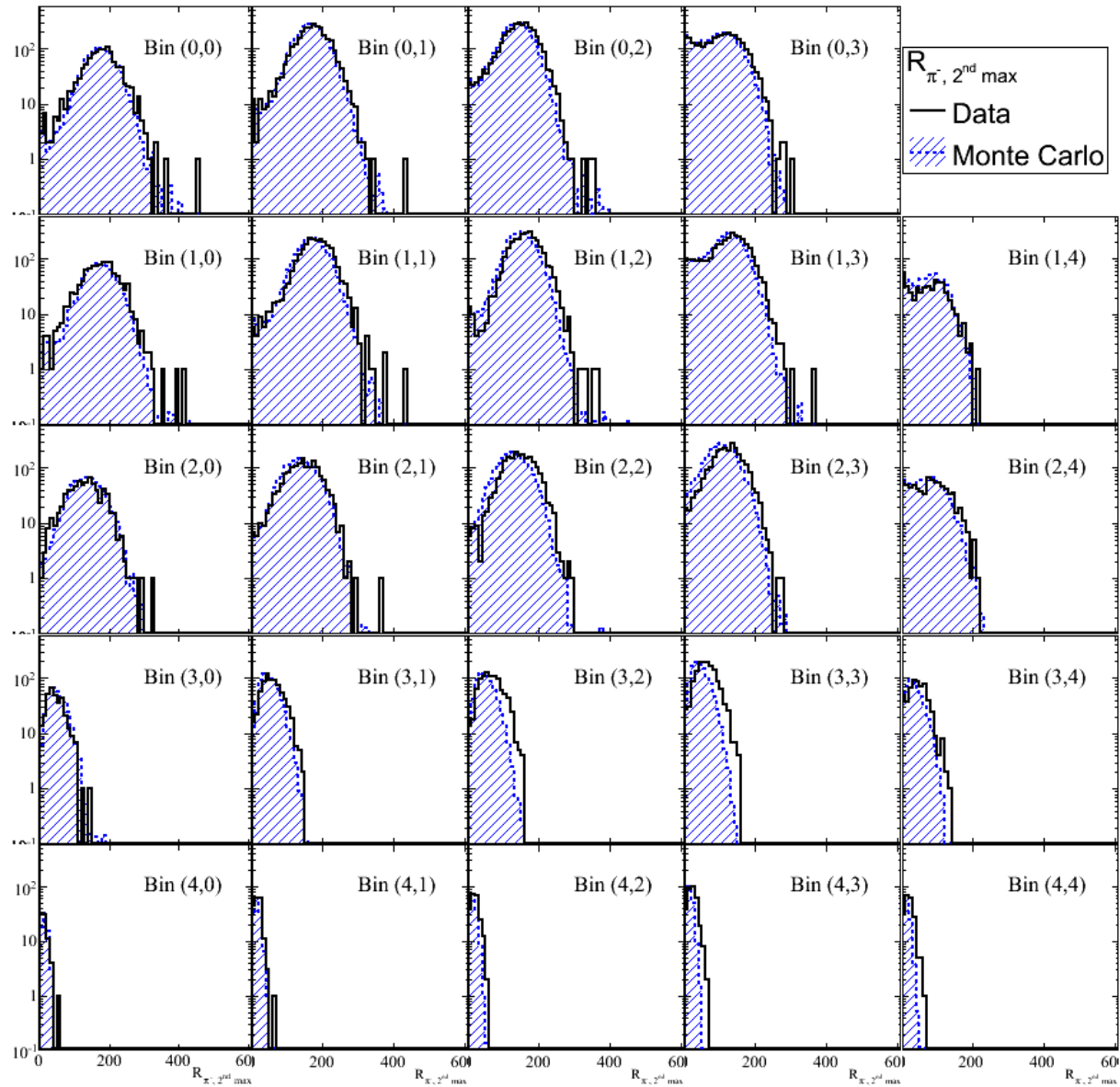
$$R_{K^- p^-} > 15 \Rightarrow \text{select } K^-$$

Optimize based on purity $\times$ efficiency

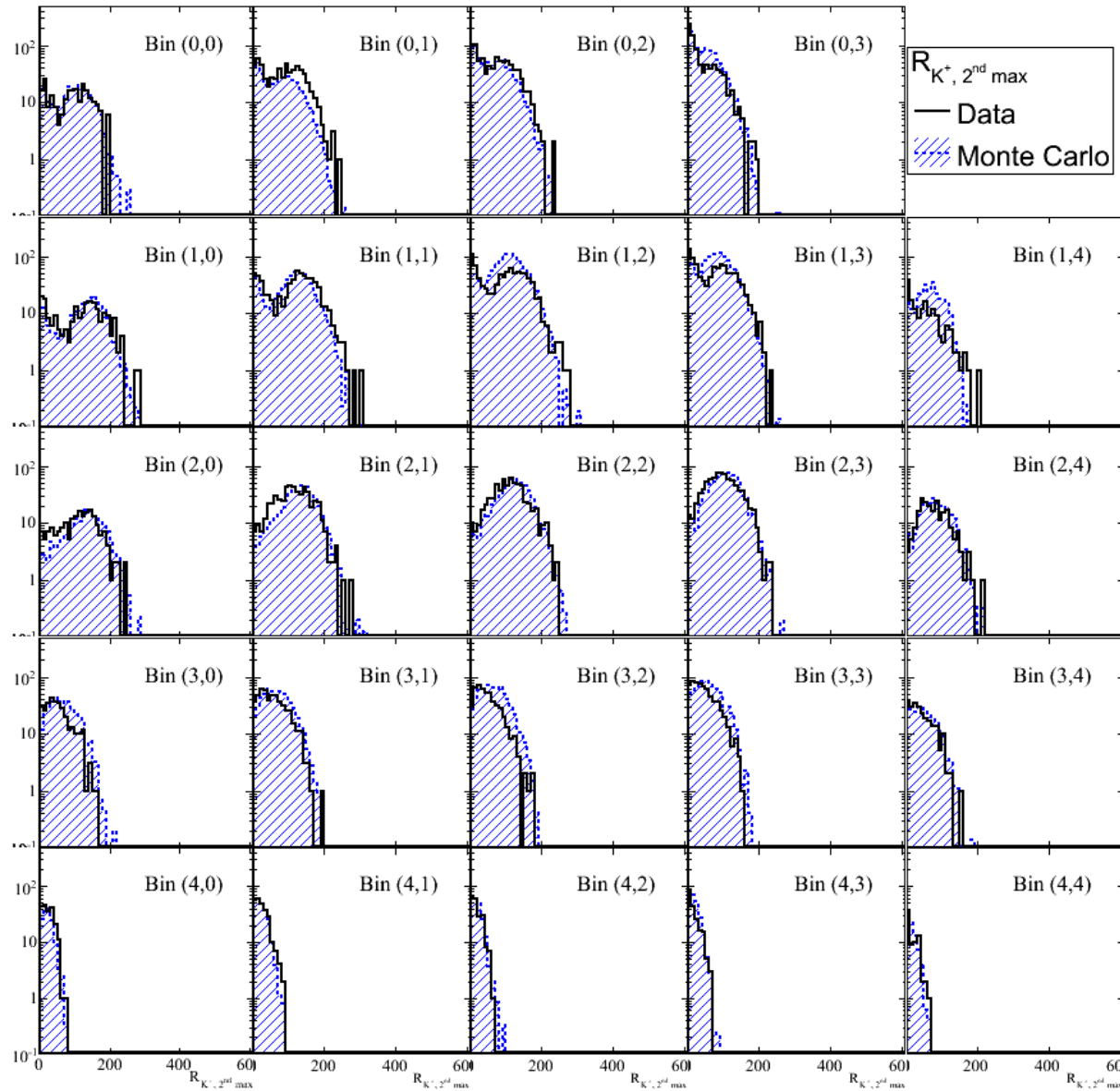
# Data/MC Comparison for $\pi^+$



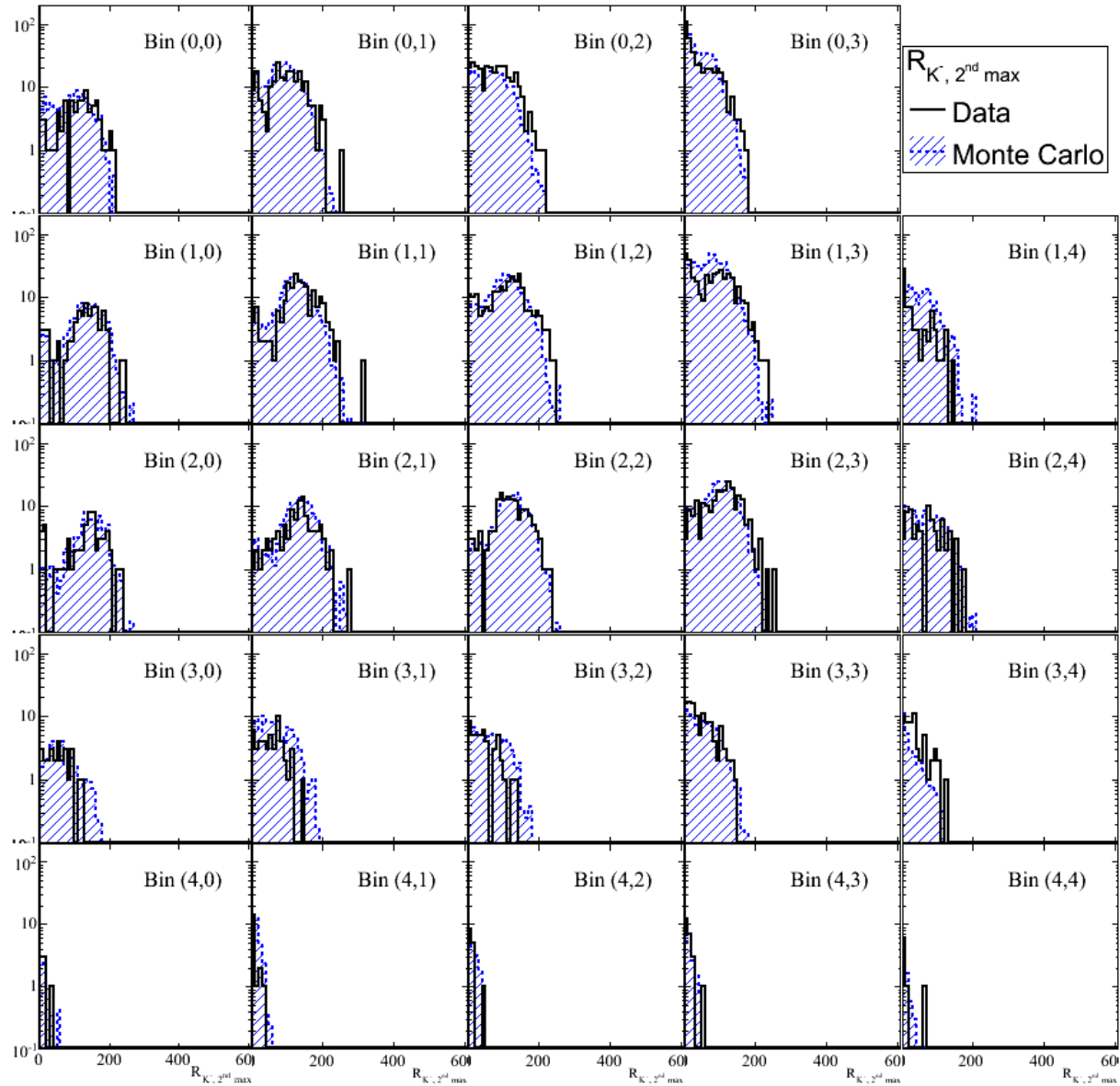
# Data/MC Comparison for $\pi^-$



# Data/MC Comparison for $K^+$



# Data/MC Comparison for $K^-$



# **Analysis Procedure**

# Analysis Overview

1. Apply corrections to extract true particle yields from data versus true momentum
2. Employ iterative approach to tune MC to look like data (background estimation)
3. Study systematic errors on the production ratios

# Evaluation of Corrections

## 1. Purity Correction, $P$

Subtract background events from selected sample

## 2. Momentum Correction, $M$

Translate a reconstructed momentum distribution to true momentum

## 3. Efficiency Correction, $E$

Accounts for events which are not correctly reconstructed by algorithms

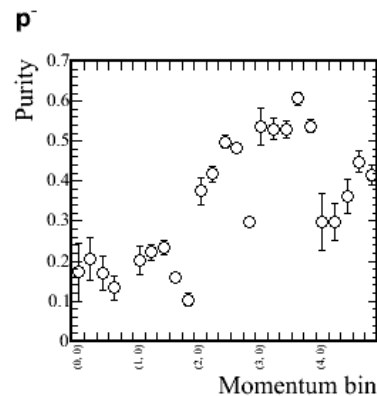
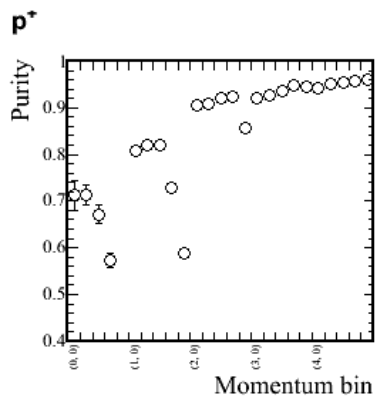
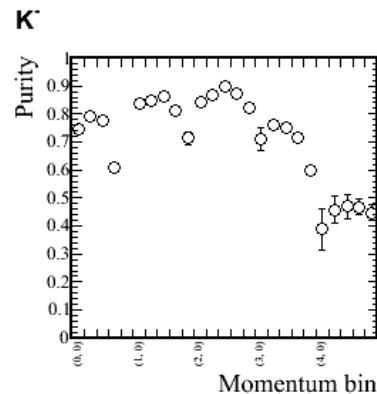
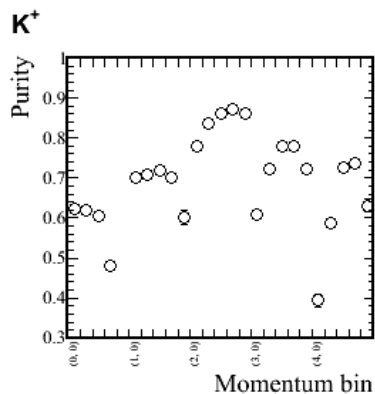
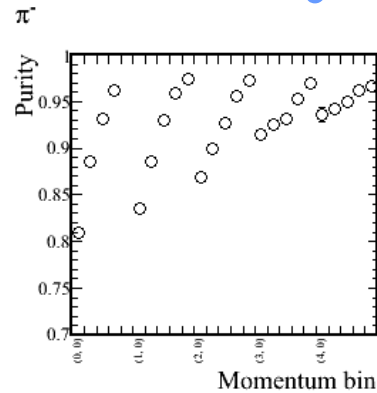
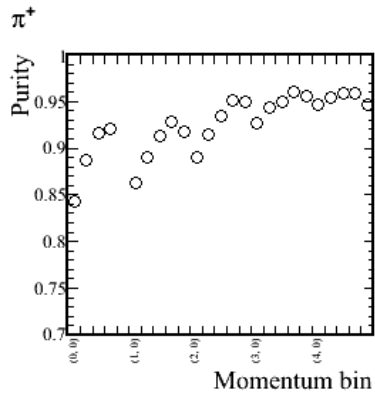
## Application of Corrections

$$N_x^j = \sum_{i=1}^{nbins} \frac{P_x^i}{E_x^j} M_x^{ij} n_x^i$$

where  $N_x^j$  = predicted # of true  $x$  in true momentum bin  $j$

$n_x^i$  = # of reconstructed  $x$  in reconstructed momentum bin  $i$

# Purity Correction



## Definition of Purity

$$P_x^i = \frac{t_x^x}{t_x}$$

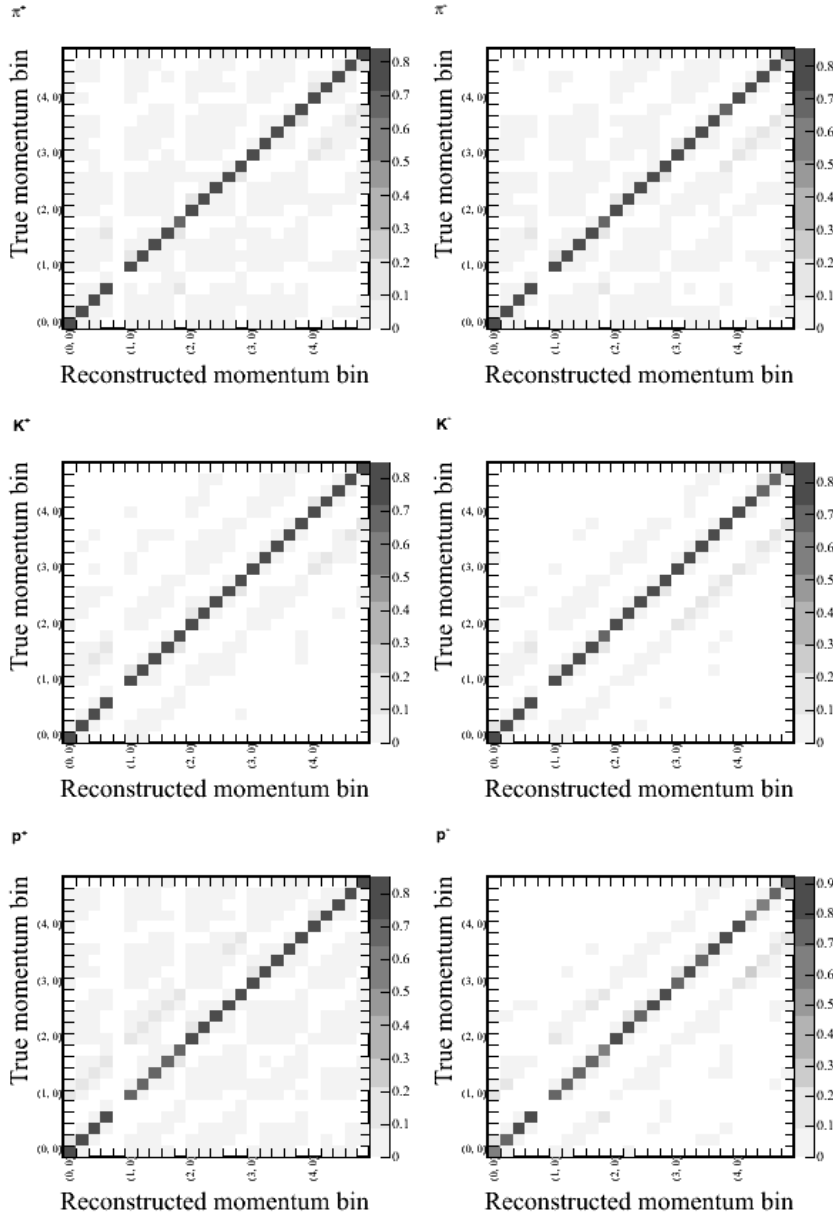
where  $t_x$  = number of reconstructed  $x$

$t_x^x$  = number of true  $x$

reconstructed to be  $x$

$i$  = reconstructed momentum bin

# Momentum Correction



## Definition of Momentum Matrix

$$B^j = \sum_{i=1}^{nbins} M_x^{ij} b^i$$

$$\sum_{j=1}^{nbins} M_x^{ij} = 1$$

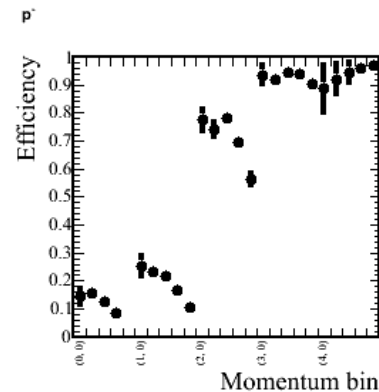
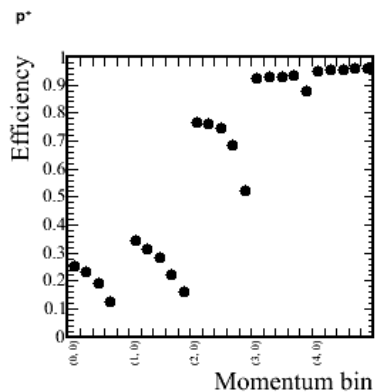
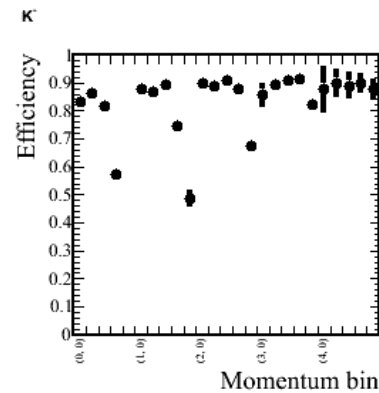
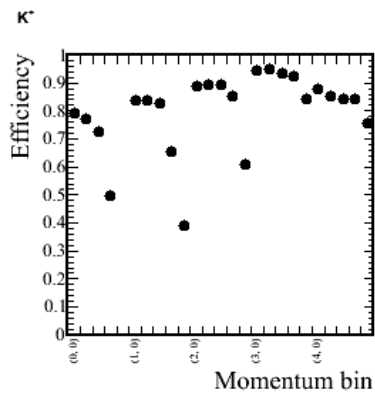
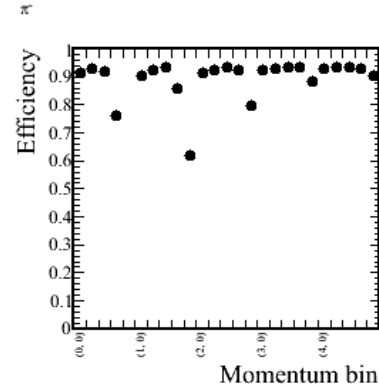
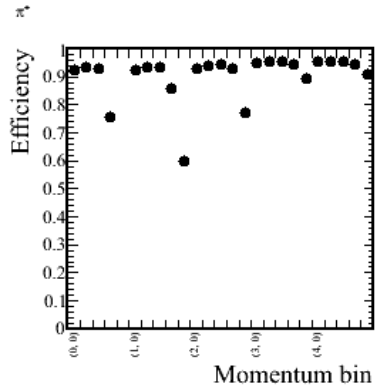
where  $B^j$  = # of events in true bin  $j$

$b^i$  = # of events in reconstructed bin  $i$

$M_x^{ij}$  = # of  $x$  to assigned to true bin  $j$

for each event observed in  
reconstructed momentum bin  $i$

# Efficiency Correction



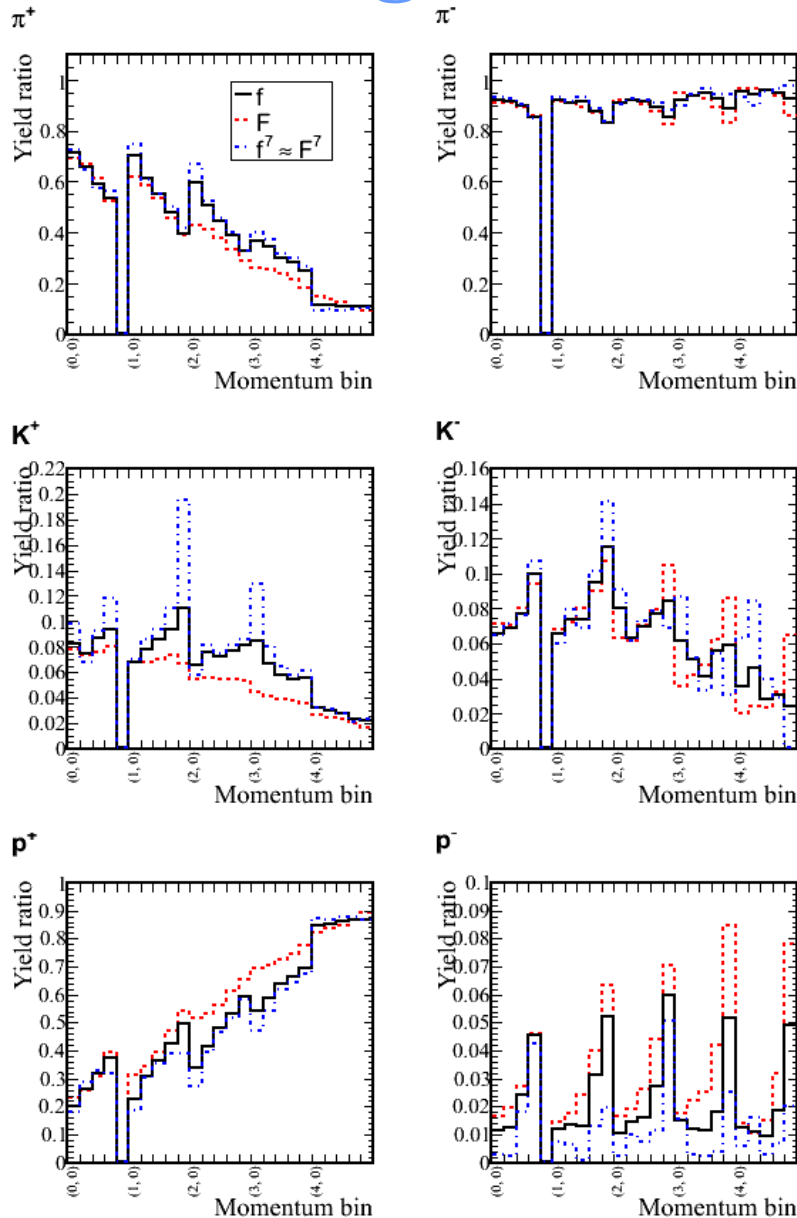
## Definition of Efficiency

$$E_x^j = \frac{t_x^j}{T_x}$$

where  $T_x$  = number of true  $x$  in MC

$j$  = true momentum bin

# Background Estimation from Data



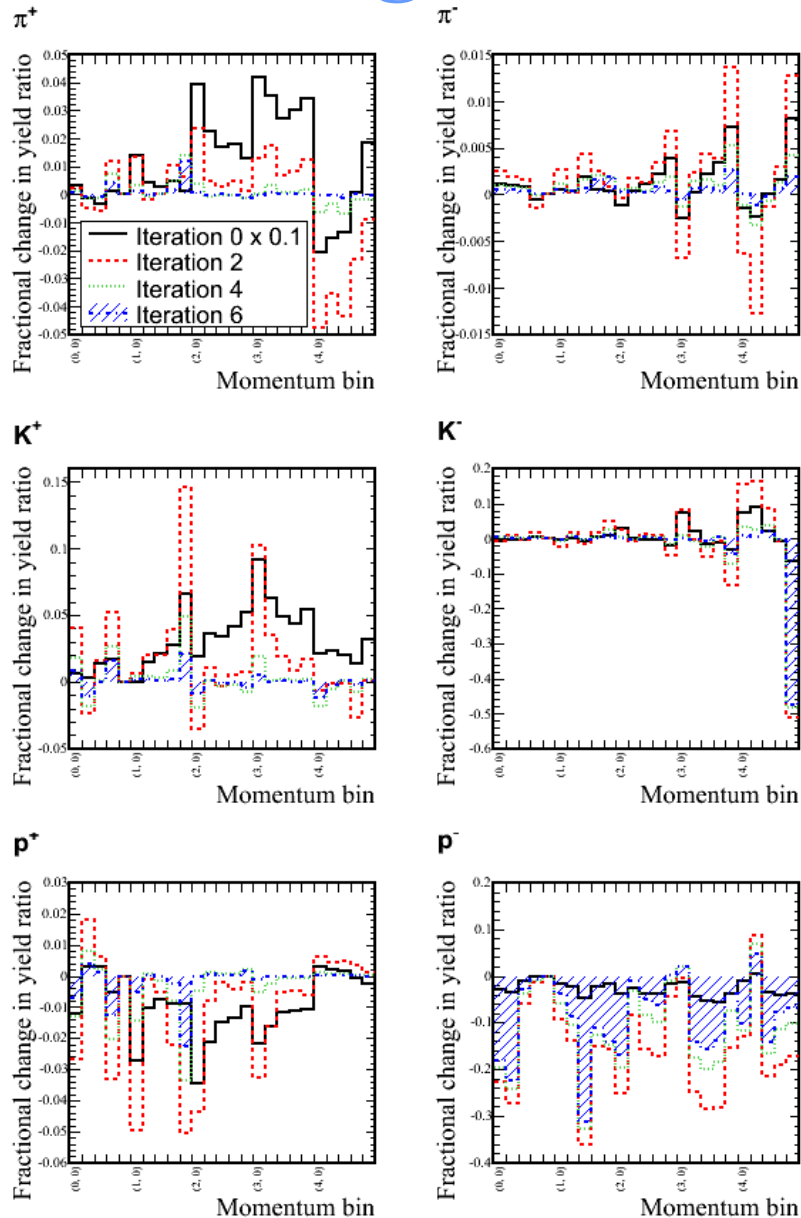
- In order to improve the accuracy of MC, an iterative, data-driven approach is adopted.
- Define yield for  $x$  from data (if  $x$  is positive)

$$f_x = \frac{N_x}{N_{\pi^+} + N_{K^+} + N_{p^+}}$$

and yield for  $x$  from MC

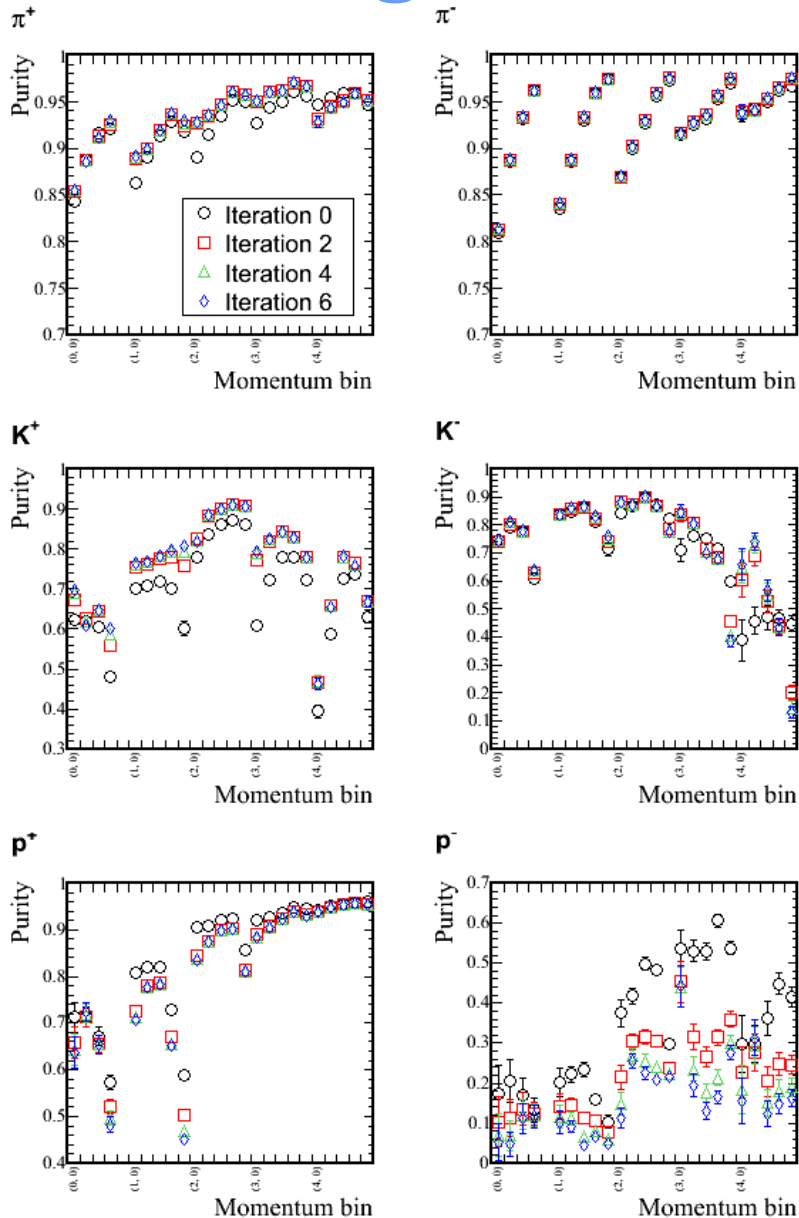
$$F_x = \frac{T_x}{T_{\pi^+} + T_{K^+} + T_{p^+}}$$

# Background Estimation from Data

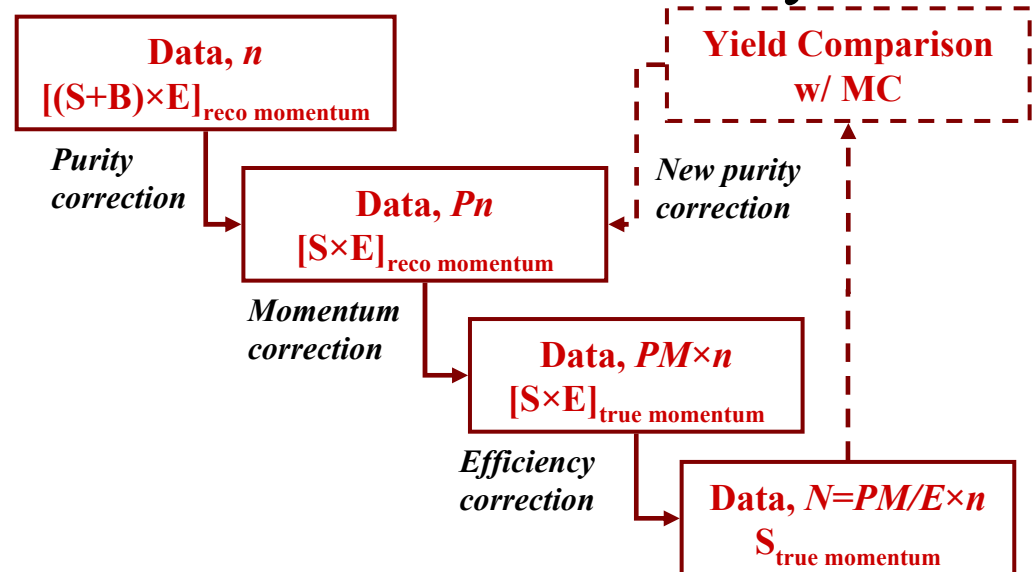


- Use data/MC yield ratio,  $w_j = f_j / F_j$ , to **reweight the MC truth in each true momentum bin**
- Change in yield ratios,  $(w_j^{k+1} - w_j^k) / w_j^k$ , between  $k^{th}$  and  $(k+1)^{th}$  iterations come to stable values and approach 0 after 7 iterations

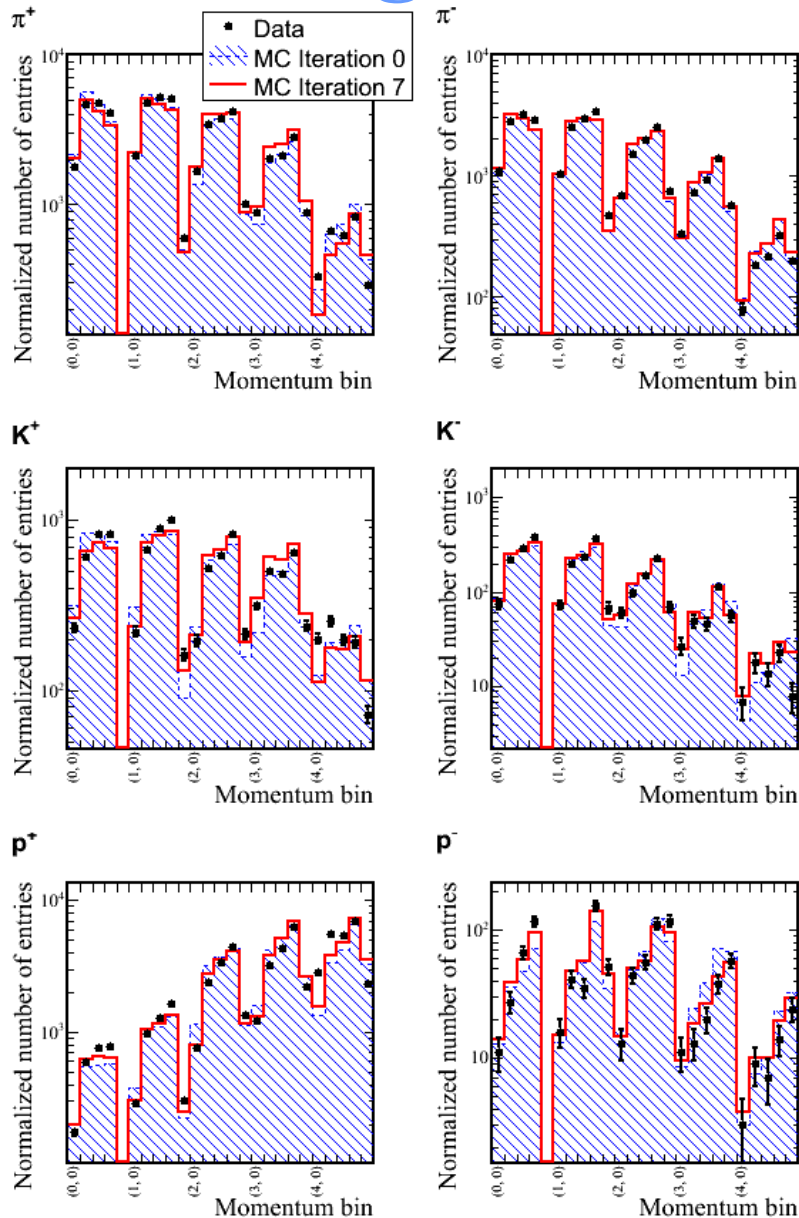
# Background Estimation from Data



- Purities of  $\pi^\pm$  and  $K^\pm$  increase, while purities of  $p^\pm$  decrease
- Note that this tuning only affects the purity, but not the efficiency



# Background Estimation from Data



Agreement in reconstructed spectra between data and MC improves after iterative procedure

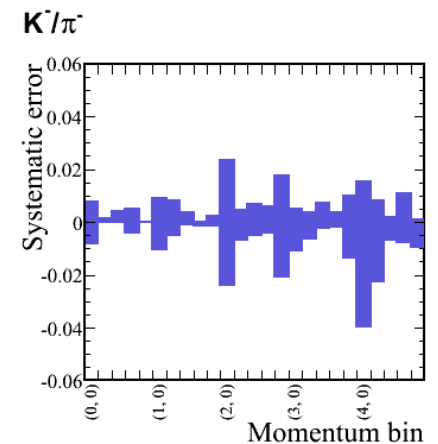
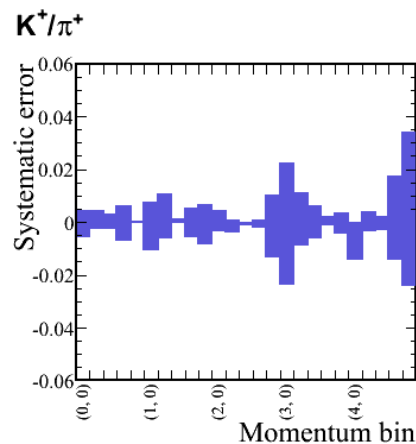
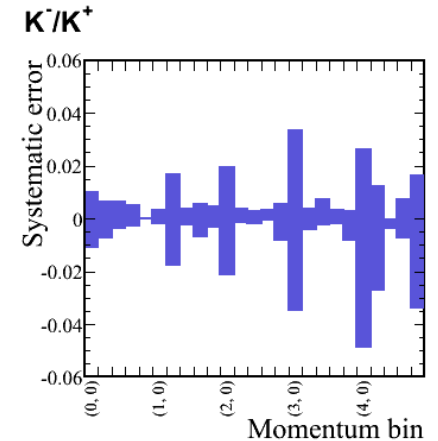
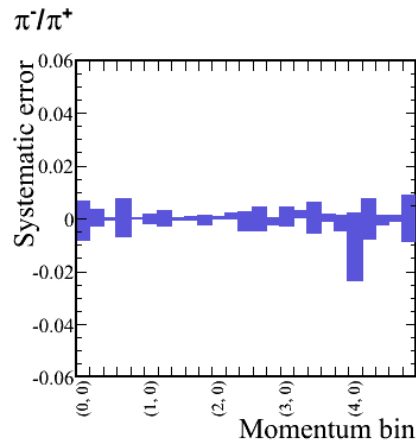
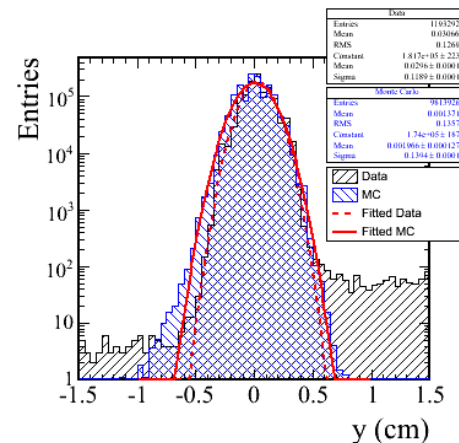
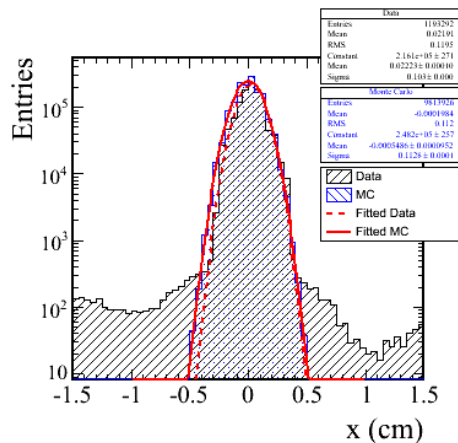
Particle	$\chi^2$ Before Iteration	$\chi^2$ After Iteration
$\pi^+$	915.06	1109.29
$\pi^-$	526.26	500.59
$K^+$	423.79	270.77
$K^-$	169.51	73.02
$p^+$	4022.47	2492.96
$p^-$	134.97	44.09
<b>Sum</b>	<b>6192.06</b>	<b>4490.72</b>

# Systematic Errors

- Effect of systematic errors on ratios have been calculate using the MC
- Estimation of systematic errors induced by
  - Beam tuning
  - Momentum bias
  - Background subtraction

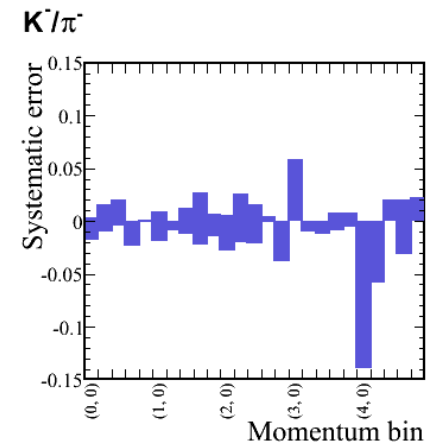
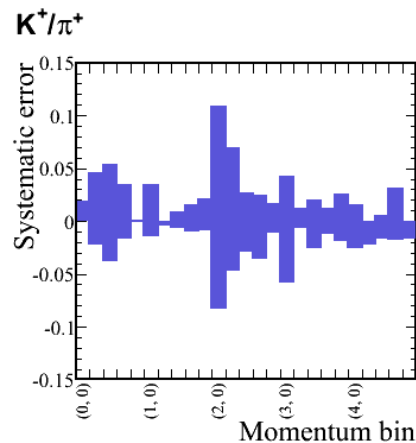
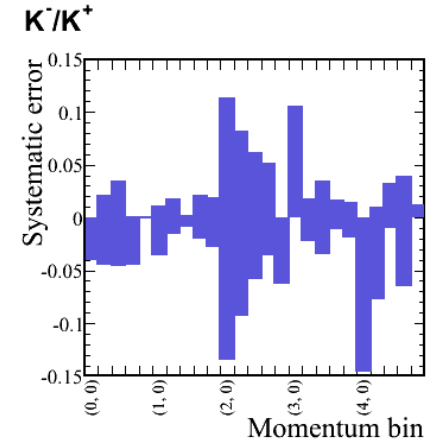
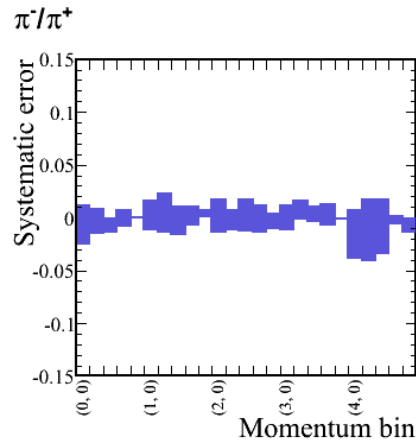
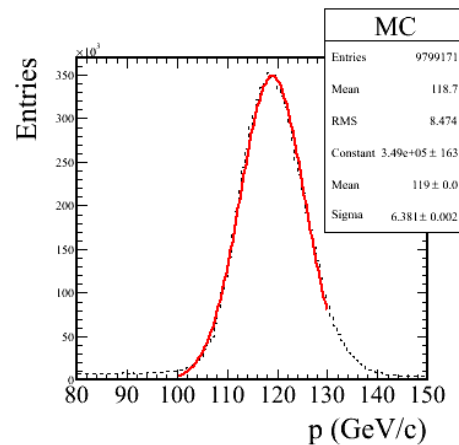
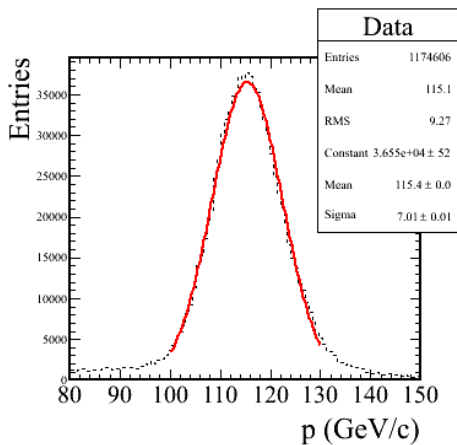
# Beam Systematic Error

- Motivation: difference between data and the MC beam width (MINOS)
- Increase/decrease beam width by  $0.1mm$  in  $x$  and  $0.2mm$  in  $y$



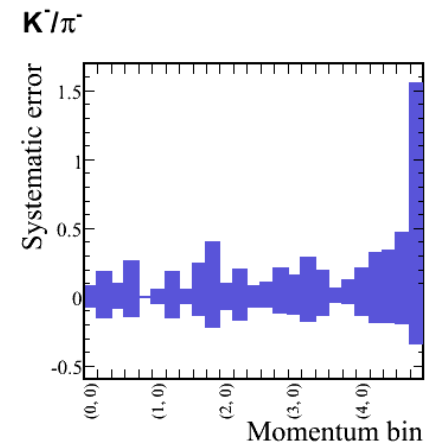
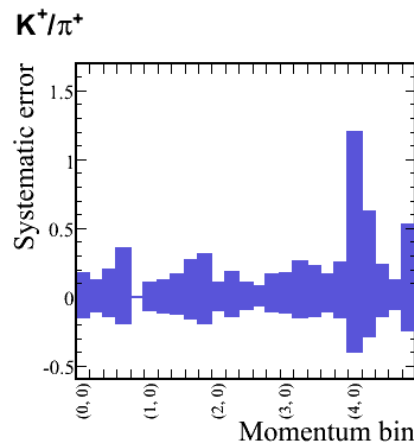
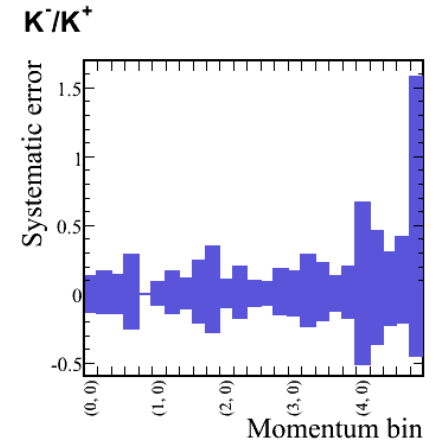
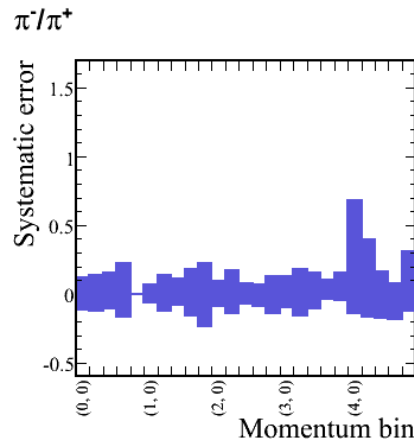
# Momentum Systematic Error

- Motivation: reconstructed momentum in data is smaller than in MC for 120GeV/c proton beam
- Increase/decrease reco momentum by  $\pm 3\%$



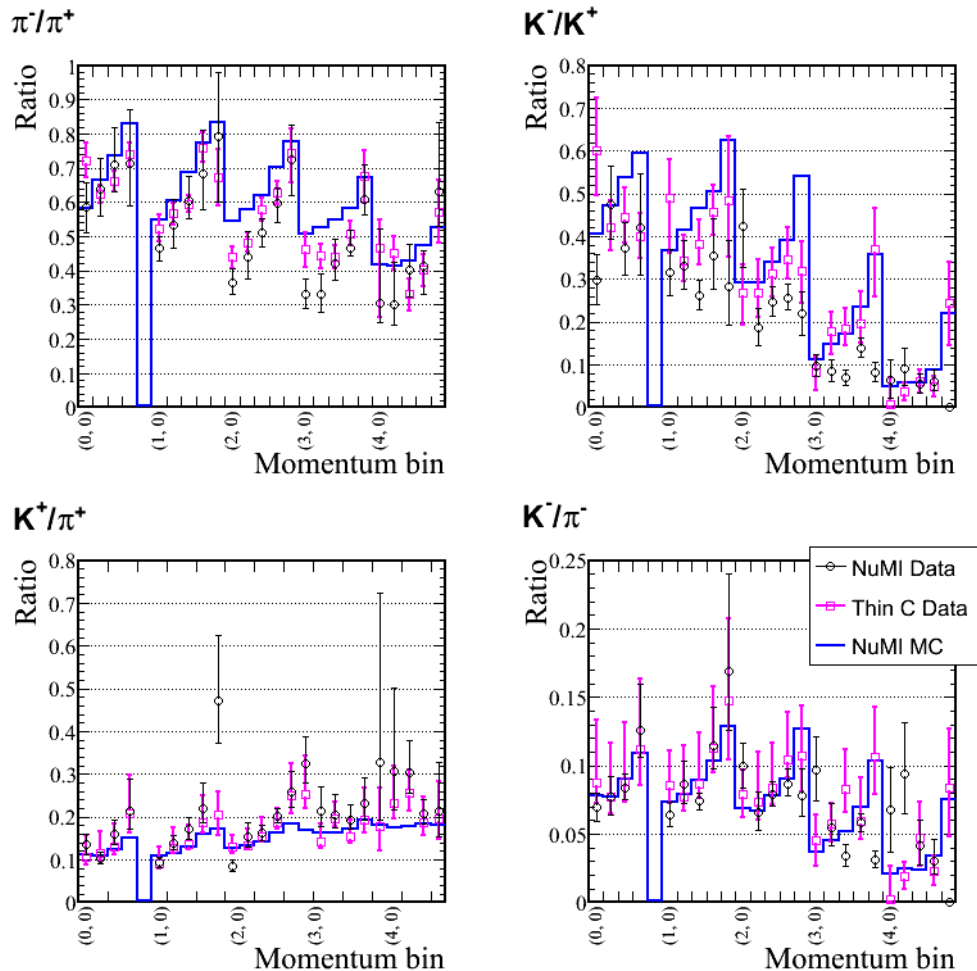
# Background Systematic Error

- Main systematic error is expected to come from background subtraction
- Procedure:
  - Normalize data/MC reconstructed momentum distribution by area
  - For each particle  $x$ , in bin  $i$  :
    - $d_x(i) = n_x^{MC}(i) - n_x^{data}(i)$
  - Background systematic error in each bin  $i$  is then given by  $\pm d_x(i)$ 
    - Translates into an error on purity correction in analysis
  - Upper and Lower systematic errors on production ratio  $x/y$  are determined by varying  $x$  and  $y$  independently
  - Upper error given by maximum change in ratio due to:
    - increase in purity on numerator
    - decrease in purity on denominator
  - Vice versa for Lower systematic error on ratio



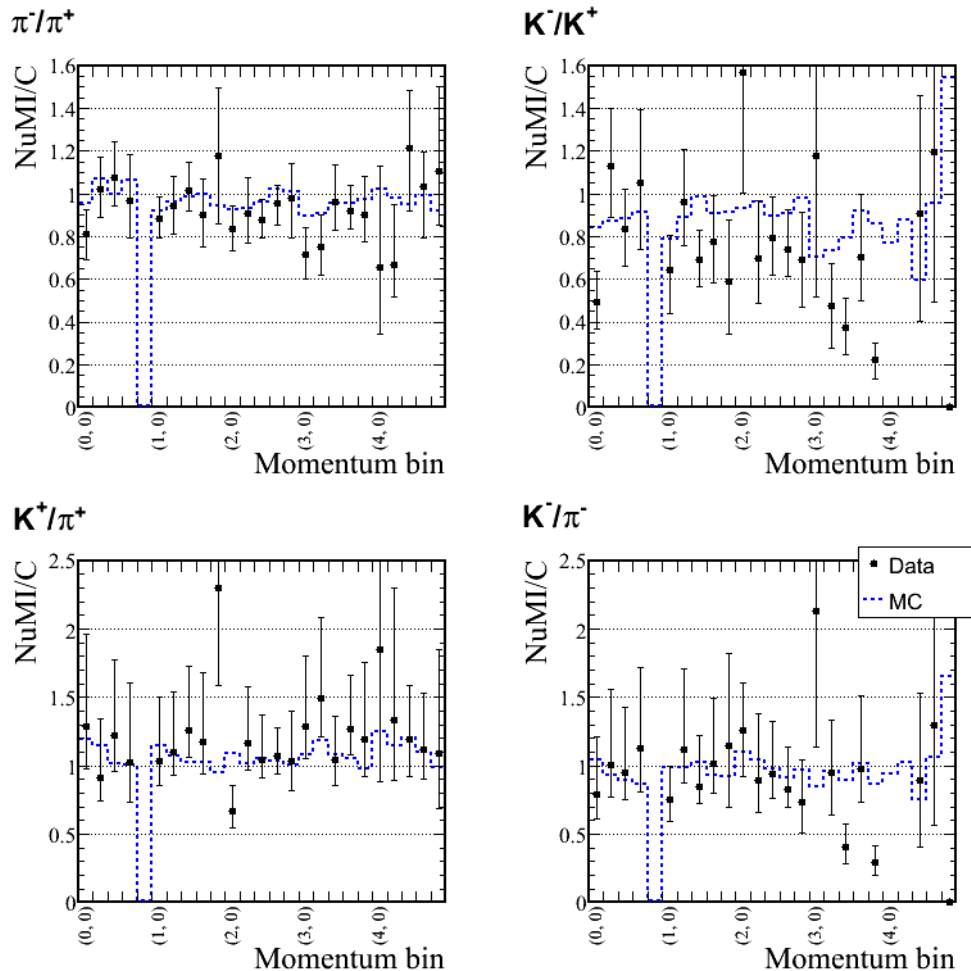
# NuMI Target Results

# NuMI Results



- Compared to MC
  - Substructure in NuMI data similar to MC
  - MC overestimates  $\pi^-/\pi^+$  and  $K^-/K^+$ , while underestimate  $K^+/\pi^+$
- Compared to C data
  - NuMI data show a steeper structure in  $p_T$  for  $\pi^-/\pi^+$  and  $K^+/\pi^+$
  - NuMI data have higher  $K^+/\pi^+$  in most bins – agree with the asymmetric error bars in C data

# Comparison for NuMI/C Data and MC

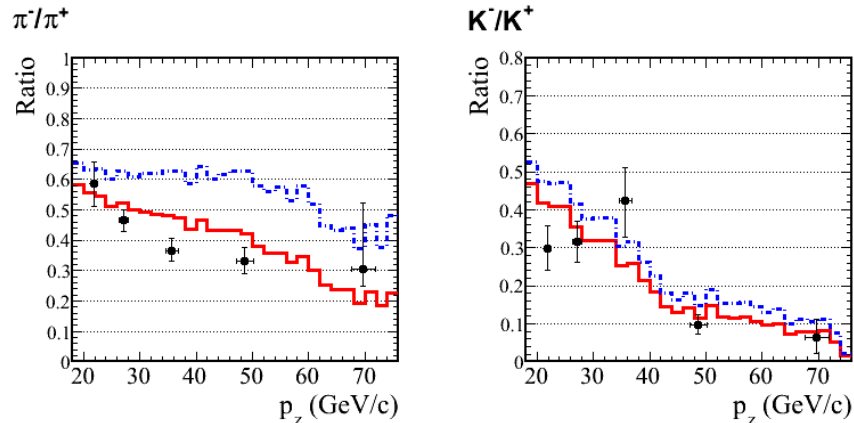


- Primary difference between NuMI and thin C expected to be effect of re-interaction in the NuMI target
- NuMI/C data and NuMI/C MC agree within errors

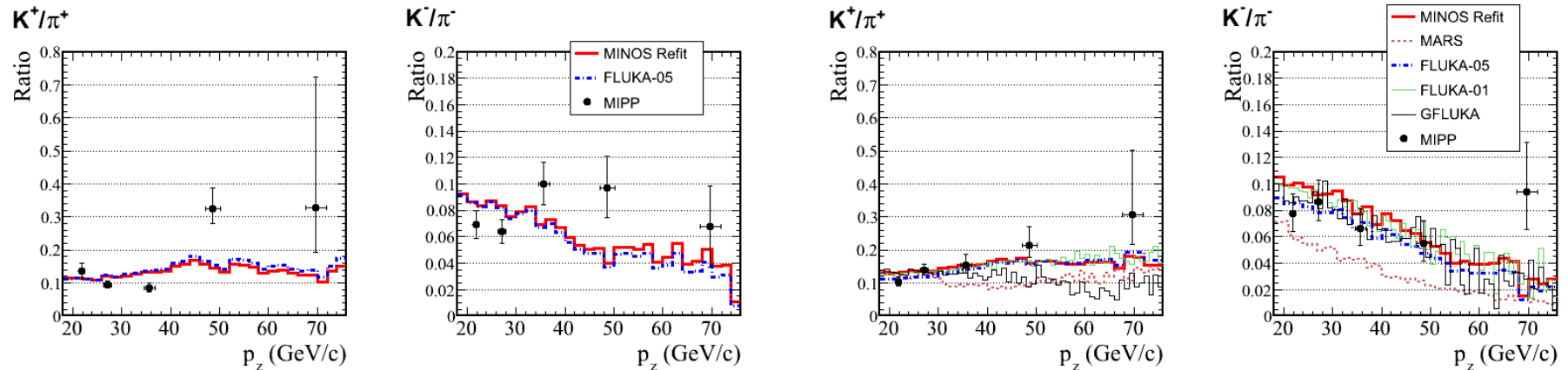
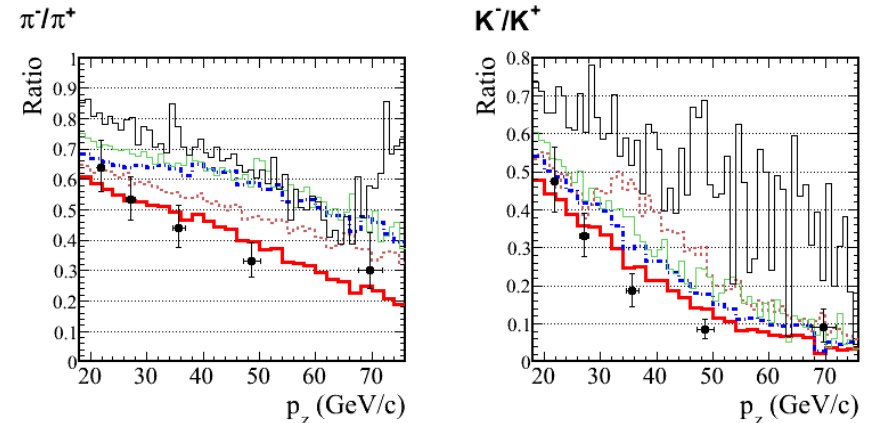
$\pi^-/\pi^+$  “suggests” that MC models extrapolate from thin to thick targets reasonably well

# Comparison with MINOS Models

$p_T < 0.2 \text{ GeV/c}$



$0.2 \text{ GeV/c} < p_z < 0.4 \text{ GeV/c}$



- Significant differences between NuMI data and MINOS MC models
- However, reasonable agreement with MINOS refit
  - Refit is driven by MINOS Near detector data
  - Primary difference:  $K^\pm/\pi^\pm$  at high  $p_z$

# Conclusions

- $\pi^-/\pi^+$ ,  $K^-/K^+$ ,  $K^\pm/\pi^\pm$  ratios for p+NuMI are presented for the high momentum region with  $p_T < 2\text{GeV}/c$  and  $20 < p_z < 90\text{GeV}/c$
- NuMI data generally agree with MINOS Refit
  - Poorer agreement with MIPP MC and other MC models
  - NuMI Data/MC ratios consistent with thin C results
- Data provide important information for neutrino spectrum prediction in MINOS from the NuMI beam, and MC hadron production models